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TRIO OF STELLAR OCCULTATIONS BY PLUTO ONE YEAR PRIOR TO *NEW HORIZONS*' ARRIVAL

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ABSTRACT

We observed occultations by Pluto during a predicted series of events in 2014 July with the 1 m telescope of the Mt. John Observatory in New Zealand. The predictions were based on updated astrometry obtained in the previous months at the USNO, CTIO, and Lowell Observatories. We successfully detected occultations by Pluto of an $R = 18$ mag star on July 23 (14:23:32 $\pm$ 00:00:04 UTC to 14:25:30 $\pm$ 00:00:04 UTC), with a drop of 75% of the unocculted stellar signal, and of an $R = 17$ star on July 24 (11:41:30 $\pm$ 00:00:08 UTC to 11:43:28 $\pm$ 00:00:08 UTC), with a drop of 80% of the unocculted stellar signal, both with 20 s exposures with our frame-transfer Portable Occultation, Eclipse, and Transit System. Since Pluto had a geocentric velocity of 22.51 km s^{-1} on July 23 and 22.35 km s^{-1} on July 24, these intervals yield limits on the chord lengths (surface and lower atmosphere) of 2700 $\pm$ 130 km and 2640 $\pm$ 250 km, respectively, indicating that the events were near central, and therefore provide astrometric constraints on the prediction method. Our coordinated observations with the 4 m AAT in Australia on July 23 and the 6.5 m *Magellan*/Clay on Las Campanas, the 4.1 m Southern Astrophysical Research Telescope on Cerro Pachön, the 2.5 m DuPont on Las Campanas (LCO), the 0.6 m SARA-South on Cerro Tololo of the Southeastern Association for Research in Astronomy (SARA), the MPI/ESO 2.2 m on La Silla, and the 0.45 m Cerro Calán telescope and 0.36 telescope in Constitución in Chile on July 27 and 31, which would have provided higher-cadence observations for studies of Pluto's atmosphere, were largely foiled by clouds, but led to detection with the LCO *Magellan*/Clay and DuPont Telescopes on July 31 of the grazing occultation of a previously unknown 15th-magnitude star, completing the trio of occultations successfully observed and reported in this paper.

Key words: Kuiper belt objects: individual (Pluto, Quaoar) – planets and satellites: atmospheres – planets and satellites: individual (Nix) – occultations

1. INTRODUCTION

Since the work of Elliot et al. (1989), observing occultations has been a crucial method of monitoring Pluto's atmosphere. Definitive "kinks" in light curves were seen for several observations of occultations, suggesting that Pluto's atmosphere contains either an extinction layer or a strong thermal gradient. The Williams College team joined with the MIT team as of the 2002 occultation (Pasachoff et al. 2005). Further observations described by Elliot et al. (2007) revealed that as Pluto moved away from perihelion, the atmosphere was growing, which implies a glacial migration pattern. We have continued our monitoring of Pluto's atmosphere using a series of occultations from the ground and with SOFIA (Person et al. 2013; Bosh et al. 2015). Using advanced astrometric calculations to determine Pluto's velocity allows precise measurements of Pluto's chord lengths based on the length of the occultation. Two or more successful observations of the same occultation permit us to more accurately determine Pluto's shape, including its atmosphere; the surface shape and size were even more accurately determined by *New Horizons* during its 2015 July flyby (for example, Stern 2015).

Four occultations by Pluto were predicted to be visible from Canterbury University's Mt. John Observatory on the South Island of New Zealand during 2014 July (Pasachoff et al. 2014, 2015). The MIT-Williams-Lowell group used updated astrometry on both Pluto and the individual candidate stars to project the path of the occultation, with error bars, onto globes of the earth (Figure 1). Mt. John observers were Pasachoff and Schiff.

2. LIGHT CURVES

Light curves for the two of our Mt. John observations that recorded occultations, made with our Portable Occultation, Eclipse, and Transit Systems (POETS; Souza et al. 2006) are shown in Figure 2. While two of the additional Pluto light curves we obtained show no sign of successful occultation observations, there is are clear dips in the light curves for Pluto on July 23b and July 24. Enlarged versions of the curves confirm the existence and significance of these dips (Figure 3).

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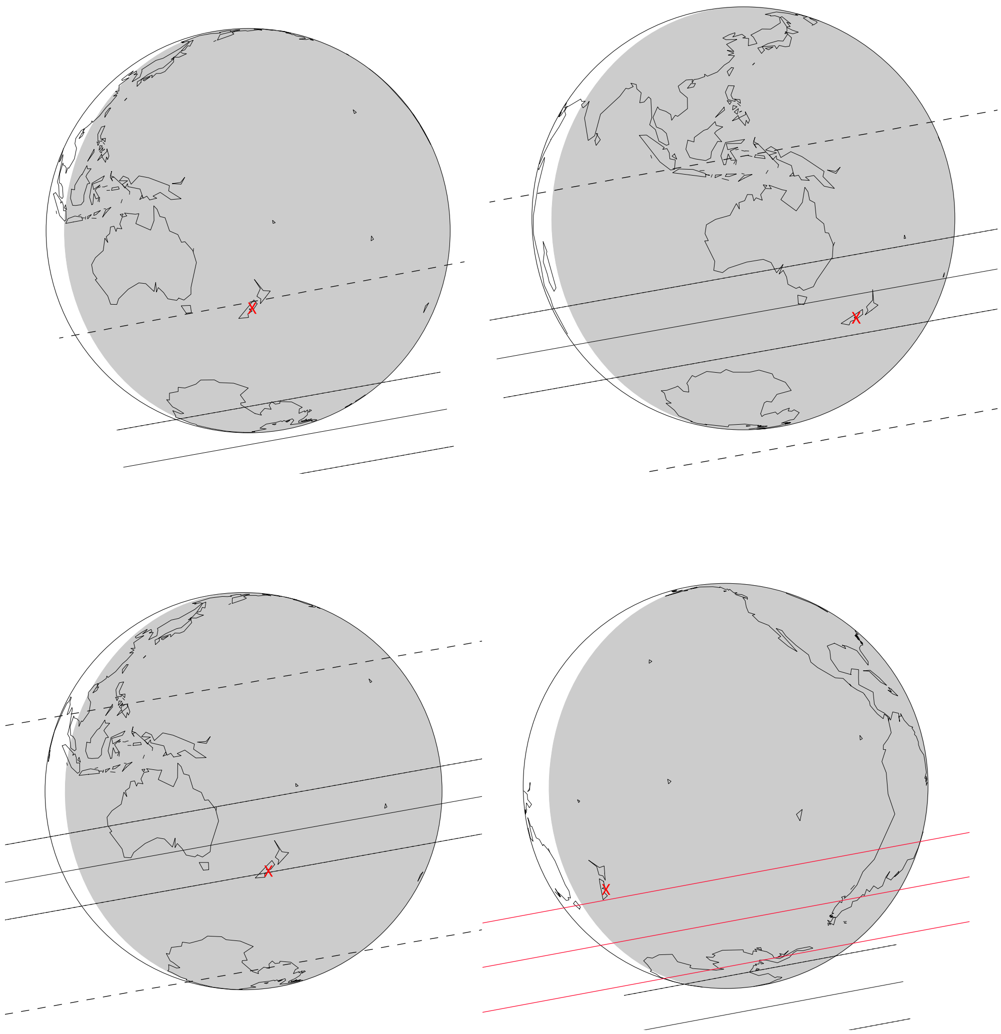

Figure 1. From left to right, top to bottom, the globes are, respectively, for occultations by Pluto on July 23a, 23b, 24, and 27, all in 2014. Mt. John Observatory's approximate location is marked as a red "x" in each image. The predicted shadow paths for Pluto are represented by three solid black lines (to indicate the northern, central, and southern locations of the shadow), and the dotted lines represent error bars on the predicted paths. The black lines represent a shadow path for Pluto, and the red lines show a prediction for Pluto with a different star, about a half magnitude fainter. A radius of 1400 km was assumed.

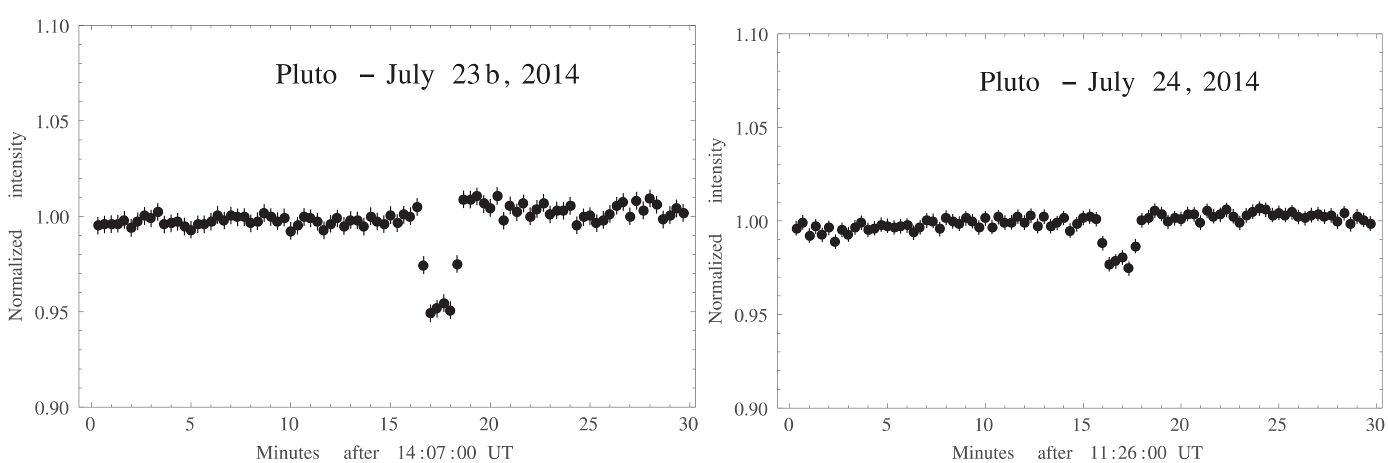

Figure 2. Light curves from the two observing sequences that detected occultations of the six observing runs at the Mt. John Observatory during 2014 July, four for predicted observations by Pluto, one for Nix, and one for Quaoar. Observing cadences were July 23 (Nix): 1 s; July 23 (Quaoar): 4 s; July 23ab and 24 (Pluto): 20 s; and July 27 (Pluto): 5 s, with 16 bit readout at 1 MHz, 2×2 binning, and a gain of 0.7 e^{-} ADU^{-1}.

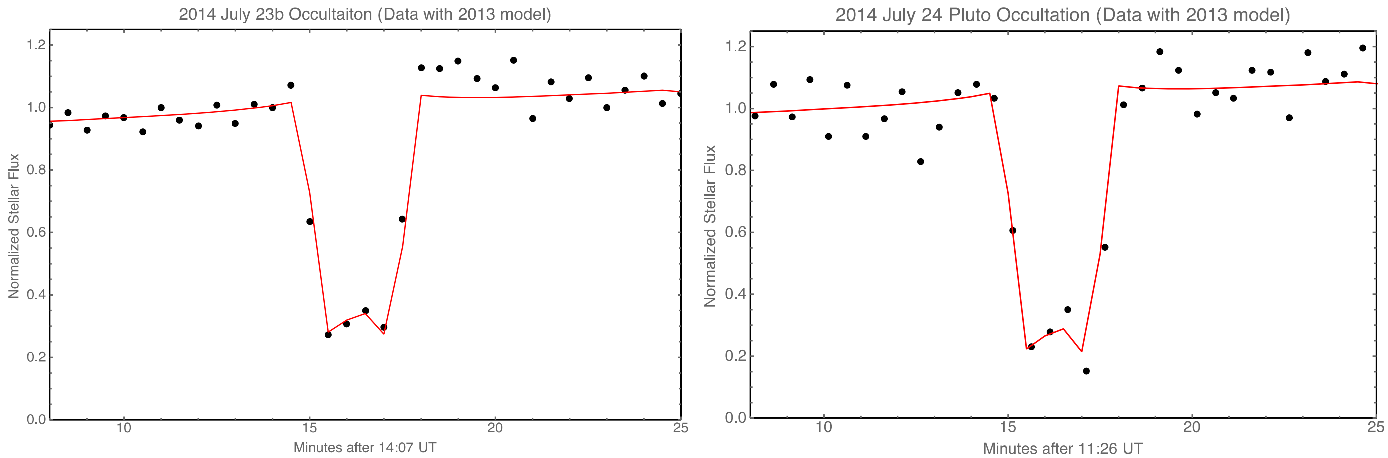

Figure 3. Enlargements of the light curves for our two successful occultation detections, on July 23 and 24, respectively. Above we plot the normalized calibrated signal level from the occultation stars. Overplotted is the 2013 model (see text) integrated to the 20 s resolution of the data. Though the 4 m Anglo-Australian Telescope was in use by our group for the event, and would have resulted in significantly higher SNR light curves, clouds prevented its observations.

The non-occulted base lines of both curves had standard deviations of 0.004. The July 23b data had an average depth of 0.951 relative intensity during occultation, while the July 24 data had an average depth of 0.979 relative intensity during occultation, so both dips are statistically significant.

The first occulted point on July 23 had a depth of 0.974 relative intensity which indicates that the star was occulted for 60% ± 20% of the exposure time, if we ignore the gradual drop off in intensity that would be produced by the atmosphere. Similarly, the last point of the dip has relative intensity 0.975, suggesting the star was occulted for 50% ± 20% of the exposure time. The observed occultation on 2014 July 23 therefore lasted from 14:23:32 ± 00:00:04 UTC to 14:25:30 ± 00:00:04 UTC. On July 24, the first occulted point has relative intensity 0.989 so the star was occulted for 50% ± 40% of the exposure time. The last point of the dip has relative intensity 0.988 so the star was occulted for 60% ± 40% of the exposure time. The observed occultation on 2014 July 24 therefore lasted from 11:41:30 ± 00:00:08 UTC to 11:43:28 ± 00:00:08 UTC.

3. A STELLAR DISCOVERY

In an event not predicted to be visible from our New Zealand site, Pluto was also to occult a relatively bright star ($m = 12$) on 2014 July 31 (UT) visible from Chile, and observed at LCO (where its velocity was 21.35 km s^{-1}) with the DuPont 2.5 m and Clay/*Magellan* 6.5 m telescopes (Person et al. 2013, 2014). We deployed to Chile using our Portable Occultation, Eclipse, and Transit Systems (each is POETS; Souza et al. 2006) on the DuPont (unbinned) and Clay/*Magellan* telescopes at 5 Hz in conventional mode with 2.4× gain and 2 × 2 binning of the entire frame, with field sizes of 31 × 42 arcsec for DuPont and 47 × 47 arcsec for Clay. Since the prospectively occulted star was significantly brighter than the stars occulted in the observations shown above and was observed with a bigger telescope, much greater time resolution was expected, but clouds came in 90 s before the occultation. Nonetheless, a 2% drop (in normalized stellar signal) just before (10 min 16 s earlier than the predicted midtime of the occultation of the brighter star) the expected (and clouded) event at the Clay/*Magellan* turned out to be an Pluto-atmospheric grazing occultation of a 15th magnitude star (Figure 4), isolated with Keck AO as part of this investigation, that had not been seen in our original occultation astrometry. (Figure 5). Since it was only about 2% deep, the occultation was apparently grazing. However, the close correspondence between the observed and modeled event indicates the reliability of the predicted atmospheric parameters.

Other sites, clouded out, from which our group attempted to observe this occultation were Cerro Pachón in Chile with the 4 m Southern Astrophysical Research Telescope (SOAR) by Levine; the MPI/ESO 2.2 m on La Silla with GROND (Greiner et al. 2008) by Servajean; Cerro Calán with one of our small CCD "PICO" systems (Lockhart et al. 2010) on an 0.45 m GOTO telescope by Jenkins; at Constitución on the Pacific coast southwest of Santiago with an 0.36 portable telescope by Rojo; Cerro Tololo with the 0.6 m SARA-S of the Southeastern Association for Research in Astronomy (SARA), operated remotely by Zuluaga; as well as Happy Jack, Arizona, with the Lowell Observatory's Discovery Channel Telescope, by Bosh.

4. DISCUSSION

Unfortunately, the faintness of the occulted stars demanded that for the New Zealand observations we use long integration times (20 s) to guarantee statistically significant results. As a result, it is not possible to measure the structure of the atmosphere with the light curves from these events. And even though we know two of the chords to be almost central from the chord lengths, no central flash could be seen at this resolution, in any case, no central flash would have been visible given the impact parameters (Table 2). Furthermore, since all other observatories that attempted to observe the events were obscured with cloud cover, it is not possible to ascertain the shape of Pluto since only one chord was measured.

However, if we assume that the basic structure of Pluto's atmosphere had remained unchanged since the 2013 Pluto occultation (Bosh et al. 2015), we can use the atmospheric parameters derived in 2013 to fit to the 2014 light curves, and constrain the impact parameters of the observed events even in the absence of supporting chords from other stations.

Table 1 gives the atmospheric parameters used in the model fits and Table 2 gives the resulting impact parameters.

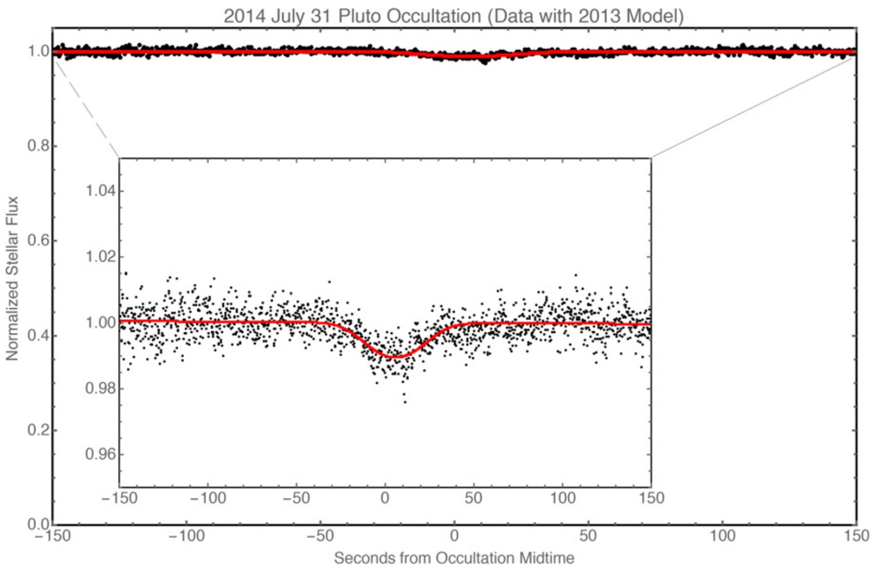

Figure 4. A light curve from the occultation of the 15th magnitude star that had been lurking unnoticed in the Airy disk of the 12th-magnitude primary star for our 2014 July 31 observations from Las Campanas Observatory in Chile, with the vertical scale enlarged in the inset. These data show that Pluto's atmosphere remains stable at this time less than one year before the passage of *New Horizons*. We see the normalized stellar flux over time from the 6.5 m Clay/*Magellan* telescope. The data are shown in black and the light curve predicted by the 2013 constrained atmospheric model is overplotted in red. Since the occultation was grazing, the drop in relative intensity is not as dramatic as that from the events observed from New Zealand. The occultation was also observed from the nearby 2.5 m DuPont telescope, though with a higher statistical noise level, given the smaller aperture. These telescopes are separated by ∼1.3 km (at 70°42′13″ W 29°00′26″ S and 70°41′33″ W 29°00′51″ S, respectively). With the sets of data, and the addition of separated photometry and careful astrometry from other telescopes including SOAR and DCT, it was possible to constrain atmospheric parameters and create the model of the occultation light curve shown. Had the ∼12th-magnitude primary star been occulted by ∼14th-magnitude Pluto/Charon, the dip would have been much more dramatic.

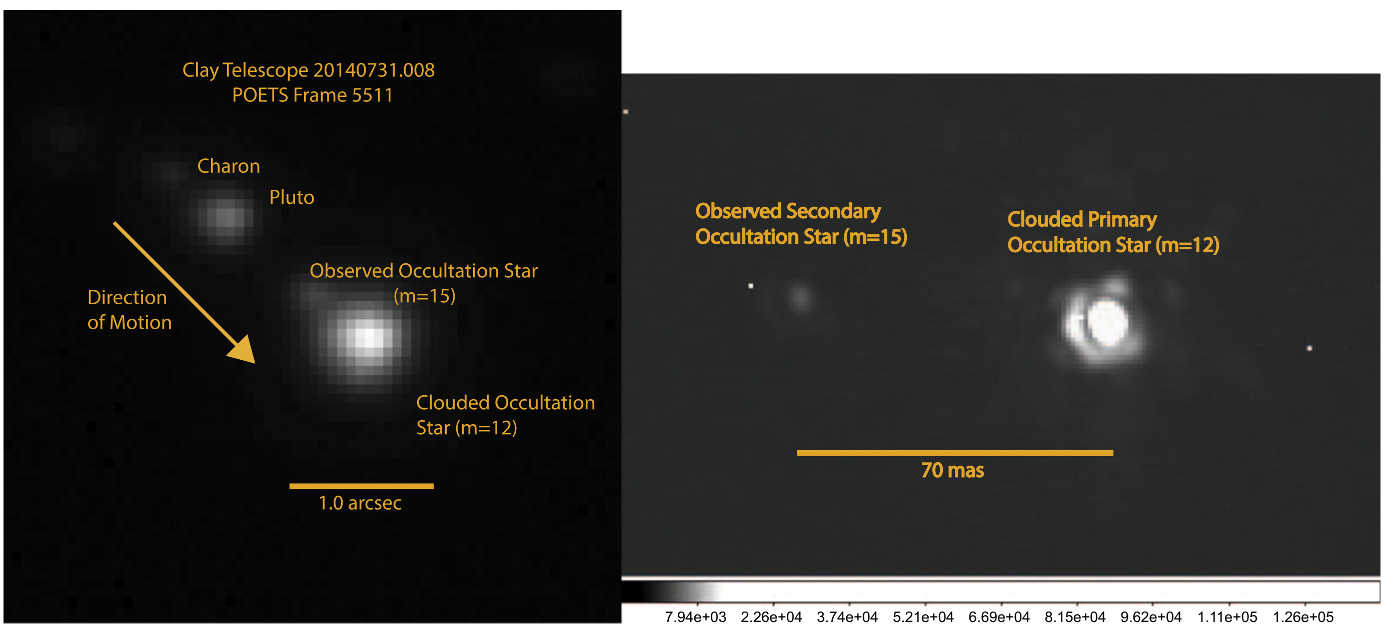

Figure 5. (a) Prior to the occultation, we see the direction of motion of Pluto/Charon toward the 12th-magnitude star, not yet known to be double. Here we display one of the highest-resolution/best-seeing frames obtained in the entire night, showing the primary and secondary stars as separable. (b) An adaptive-optics image taken with the Keck Observatory revealed at left the 15th magnitude star well separated by the 12th-magnitude star at left-center. The sharp white dots are cosmic-ray hits on the detector.

Atmospheric parameters were derived from model parameters according to the Elliot & Young (1992, EY92) methodology.

The successful observation of the occultation verified our prediction methods and provided astrometric data available for our 2015 June 29 occultation observations and for *New Horizons*'s 2015 approach.

For the July 31 event, though for our atmospheric studies we are glad to have detected the occultation of this 15th-magnitude star, actually finding the star in AO and thus ruling out the possibilities of rings or debris in the Pluto system was disappointing.

The consistency of the data with the results from the 2013 event indicate that Pluto's atmosphere had not undergone and

Table 1
2013 Model Parameters Used in Fitting

EY92 Symbol	Bosh et al. (2015) Value	EY92 Parameter Description
$r_{h,s}$	1188.7 km	Half-light radius (shadow plane)
H_p	54.4 km	Pressure Scale Height (half-light)
P_h	1.66 μbar	Pressure at half-light
T_h	94.6 K	Temperature at half-light
dT/dr	-0.24 K km^{-1}	Temperature Gradient
r_h	1299.2 km	Half-light radius (planet plane)
λ_h	17.2	Thermal Energy Ratio at Half-light
b	-2.2	Thermal Gradient Exponent

Table 2
Resulting Impact Parameters

Impact Parameters (km)	Predicted (km)	Fitted (km)
Jul 23b Event—Mt. John	668	480 ± 120
Jul 24 Event—Mt. John	1059	510 ± 140
Jul 31 Event—LCO	N/A[a]	1305 ± 68

Note.
[a] Note that the observed LCO occultation was unexpected, and thus there was no predicted value for its impact parameter.

significant changes, although continuation of the slight growing trend in atmospheric half-light size reported in 2013 may have continued and would have been hidden in the error bars of the 2014 events. Models of the occultation indicate that atmospheric pressure and radius have remained relatively stable over the past half-decade, and predict that a substantial atmosphere will be present upon the arrival of *New Horizons*.

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